



Lightweight CNT Cables for Aerospace

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NESC NDE Technology Assessment
NASA NDI Workshop
Johnson Space Center Houston, TX
February 29 & March 1, 2012



“Lightweight CNT Cables”

Purpose of This Presentation is to Inform You How.....

**Substitution of copper
with CNT can reduce
the weight of aerospace
cables.**

...CNT = carbon nanotube...

...aerospace cables = COTS = Commercial Off the Shelf cables...

...performance of lightweight CNT cables meets or exceeds that of COTS



“Lightweight CNT Cables” Objectives



- Introduce the lightweight CNT wire and cable to valued customers for light weight applications.
- Identify unique properties added to wire representative of value to the market place
- Briefly review CNT properties and performance to frame a mindset for determining if CNT fits in your “envelope of application”.
- Stimulate interest and collaboration.



“Lightweight CNT Cables” Presentation Agenda



- Introduction
- Objectives, Value Proposition & Feasibility
- Background of Present CNT Interest
- Growing Need for Lightweight Cables
- Materials Enable Lightweight Cables
- CNT Materials: Yarns and Tapes
- Wire Processing
- Lightweight CNT Cables
- CNT Cost
- MNW’s Mission: “Add Value to Wire”



“Lightweight CNT Cables” Origin of Present CNT Interest



- MND has been in “nanotechnology” for 8 years
- Application of nanocomposites, nano-coatings and pure CNT for EMI shields and conductors
- Introduced stretchy wire and shields
- Prior developments in medical and aerospace wire integrity
- Funding from defense SBIR Grants & prime contractors
- Collaboration with defense agencies & primes
- Built a development methodology to design and process CNT cables compliant with aerospace requirements.



“Lightweight CNT Cables”

Growing Need for Lightweight Cables



– Market desire for network-centric operations

Infrastructure moves toward connectivity as that is the nature of progress:

- Increases incorporation of more electronic systems
- Growing presence of more cables leads to concern over EMI protection

– Usage Logistics for vehicle apps

Reduced weight translates to a number of significant economic and operational benefits, including:

- Improved operating range and time-on-station capabilities
- Capability to carry larger payload
- Reduced in-theater logistics for fuel management
- Economic saving from greater fuel efficiency

One area of significant opportunity for increased weight savings is wiring. All of this drives the value for lightweight cables.



“Lightweight CNT Cables” Introduction: Who is Minnesota Wire?

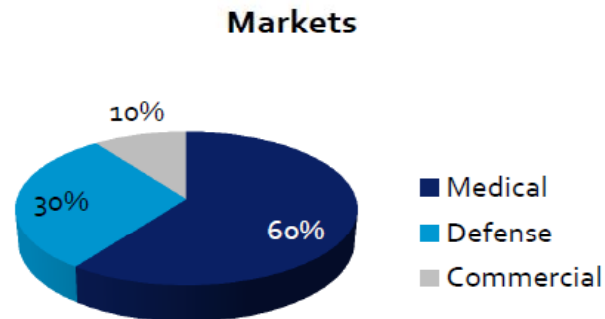


**HQ and R&D
St Paul, MN
28,000 sq ft**



**Manufacturing Center
Eau Claire, WI
58,000 sqft**

Minnesota Wire is a vertically integrated, custom manufacturer of wire, cable and interconnect assemblies.



Minnesota Defense is a division of Minnesota Wire



“Lightweight CNT Cables” R&D Laboratory Capabilities

Mechanical Lab

- tensile, multi-flex, multi-impulse
- precision weight scales
- Fused Deposition Modeling
- utilize NRTL's for environmental & HALT

Signal Integrity Lab

- precision electrical measurement
- high frequency measurement
- signal & data integrity platforms

EMC Lab

- shielding effectiveness

Nano Technology Lab

- CNT process development
- wet chemistry
- Super Critical Fluid, RESS

Imaging Lab

- FLASH digital scope
- electron microscopy access UofMN for TEM, SEM-EDS, XPS, Confocal Raman, AFM

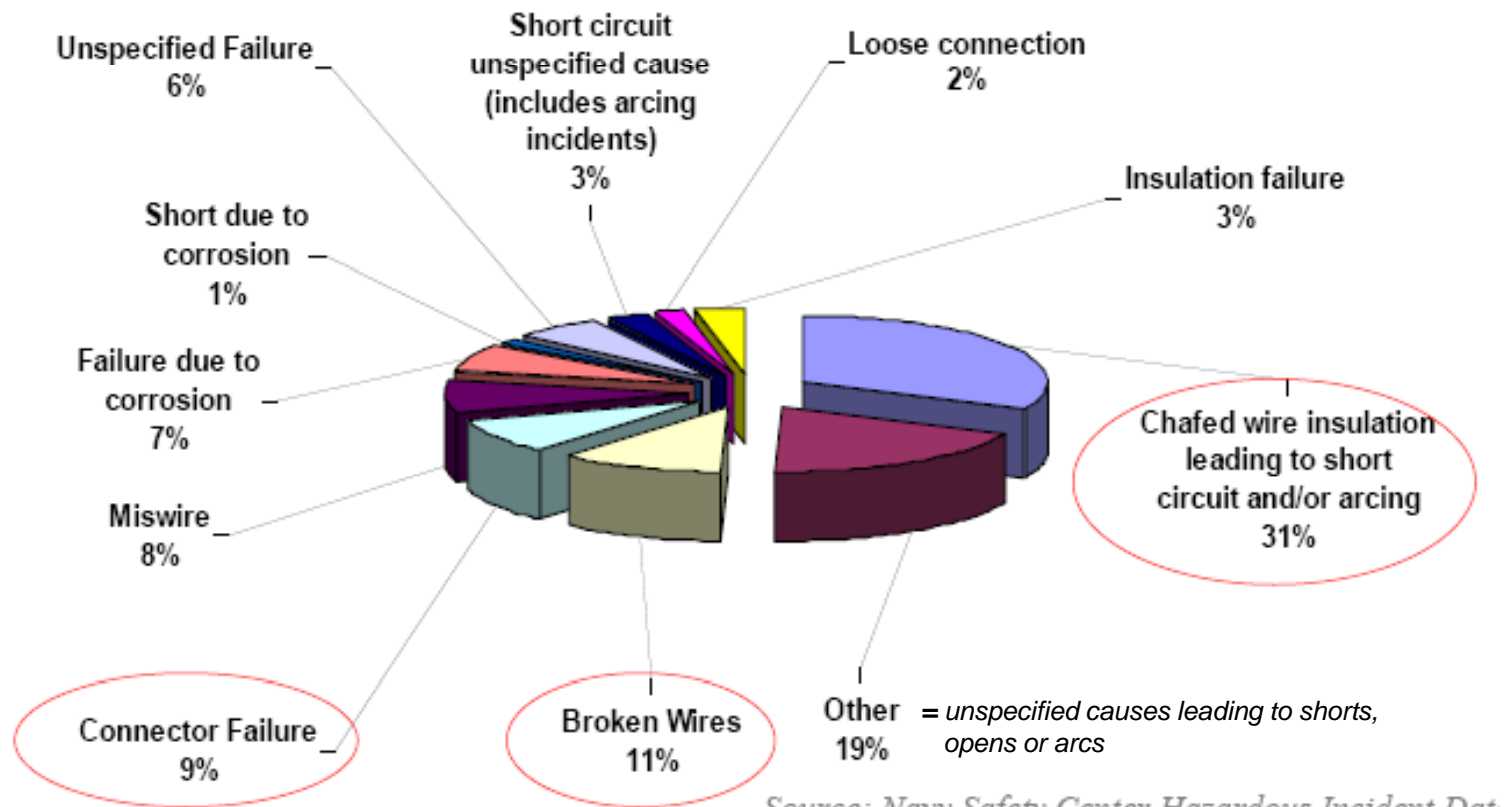


“Lightweight CNT Cables” Aerospace Wiring Capabilities

- Braiding, twisting, serving of conductors
- Wrapping of tapes, foils, insulations, dielectric
- Polyimide wrapping & sintering
- Fluoropolymer extrusion: ETFE, PFA, FEP
- Mil-spec terminations and over molding
- Automation for high volume lines



“Lightweight CNT Cables” MND Development History in Aerospace Wire Integrity **TYPICAL WIRE FAILURE MODES**



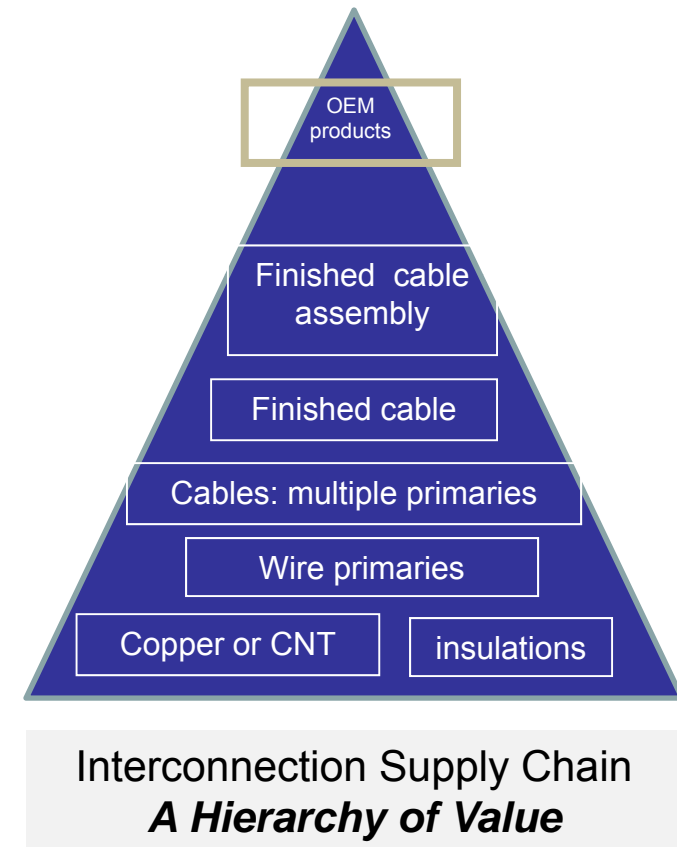
Source: Navy Safety Center Hazardous Incident Data



“Lightweight CNT Cables” Nanotechnology for Electrical Conductors and Shields Strategy



- Introduce unique properties of nanotechnology integrated cables into the interconnection (wire and cable) market for value added performance
- Leverage integration of hybrid conductors into the mainstream interconnection market thru development of nano-based electrical conductor technologies for high-end aerospace, medical and commercial market applications
- Substitute CNT for copper in niche as well as mainstream markets where conductivity performance is acceptable
- Develop partnerships for advanced technology transfer for value added integration and application



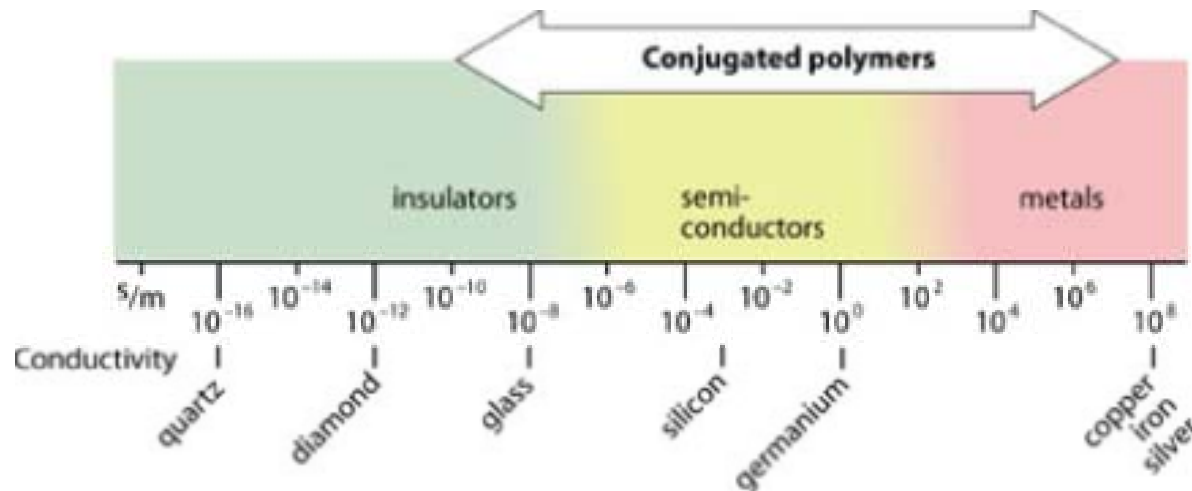


“Lightweight CNT Cables” Nanocomposites and CNT

- Are mixtures of nanomaterials like CNT (carbon nanotubes) and a polymer either in liquid or solid processing techniques
- EMI applications examples include plastic shielded electronic enclosures, transparent display coatings, elastomeric shields for stretchy wire, etc
- Applications are limited due to the low electrical conductivity
- The CNT products of *yarns* for wires and *tapes* for shielding material are more “pure” CNT
- This process involves making the CNT’s and converting them into finished product simultaneously so they are potentially more conductive by nature

“Lightweight CNT Cables” Conductivity is the Goal Experienced Challenges

- Polymer composites of SWCNT's achieve conductivity for few applications beyond ESD or EMI shielding, certainly no where near copper $60 \times 10^6 \text{ S-cm}^{-1}$ for electrical power conductors
- Intrinsically conductive polymers like polyacetylene, polyaniline, polythiophene and polypyrrole have been recorded to have reached levels up to 10^5 S-cm^{-1} but they are impractical or unavailable
- A practical choice for coatings is silver conductive ink at $17 \times 10^{-6} \Omega\text{-cm}$, or $5 \times 10^6 \text{ S-cm}^{-1}$



Nobel Prize Work : A Heeger, A MacDiarmid, S Shirakawa

“Lightweight CNT Cables” CNT Materials: Yarns and Tapes



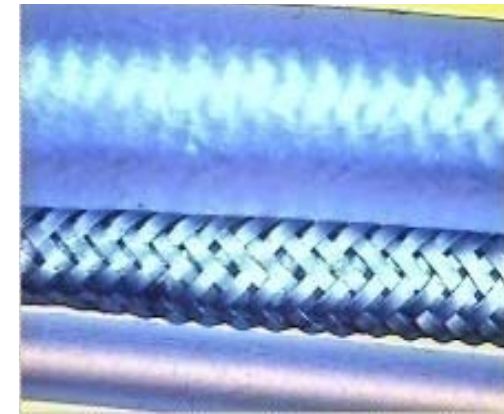
CNT yarns and sheets are fabricated into braided constructions for conductors and shielding tapes respectively for key electrical cable components that are OEM purchased.

“Lightweight CNT Cables” Wire Processing With CNT Braiding Conductor



The Braider

braids CNT yarns peripherally around a center core of multiple CNT yarns to essentially fabricate a conductor



“Lightweight CNT Cables” Wire Processing With CNT Fluoropolymer Insulation Extrusion

Davis Standard
Fluoropolymer Wire Extruder
for application of FEP, PFA, ETFE
insulations

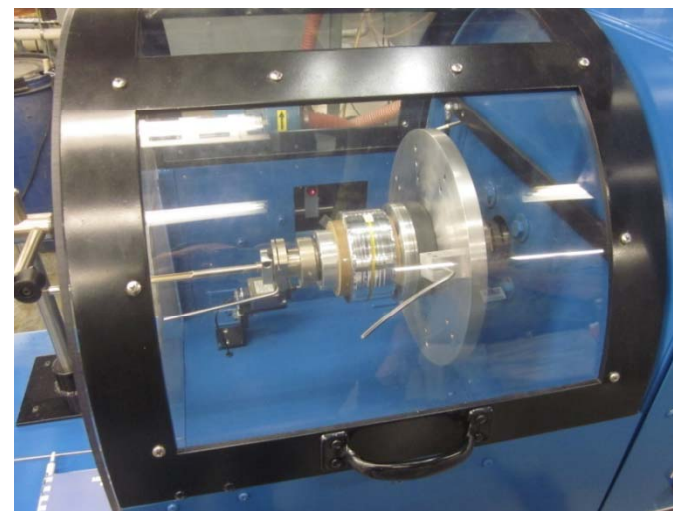


ETFE insulated conductor primary for CAN
Bus & RS485 cable
ready for fabrication, assembly and
impedance optimization for twisted pair
transmission lines

“Lightweight CNT Cables” Wire Processing With CNT Wrapping CNT Tape and Insulation



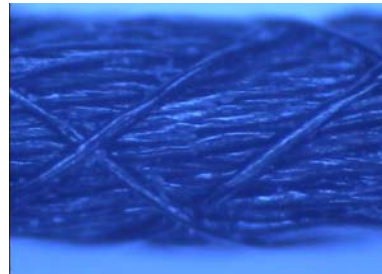
The "ejr" Wrapper
for Kapton/Oasis wrap and sinter insulation this is a 50 foot machine with payoff, 2 head wrapper, 10' sintering oven and take up.



“Lightweight CNT Cables” Wire Processing With CNT Finished Cable Assembly



CNT Yarn



Braided conductor



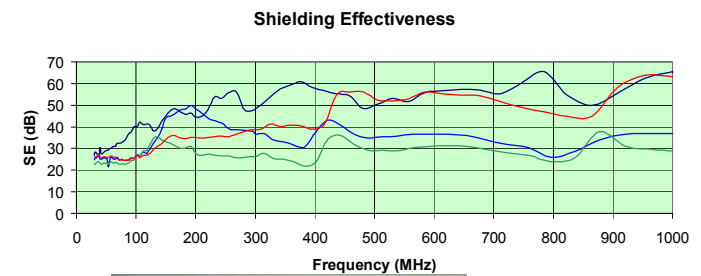
Conductor braiding



CNT tape



CNT twisted pair cable



CNT Coax



“Lightweight CNT Cables”



Conductor Material Performance Attributes

- Conductivity**
- Tensile**
- Flex life**
- Weight advantage**
- General aerospace wire standards**

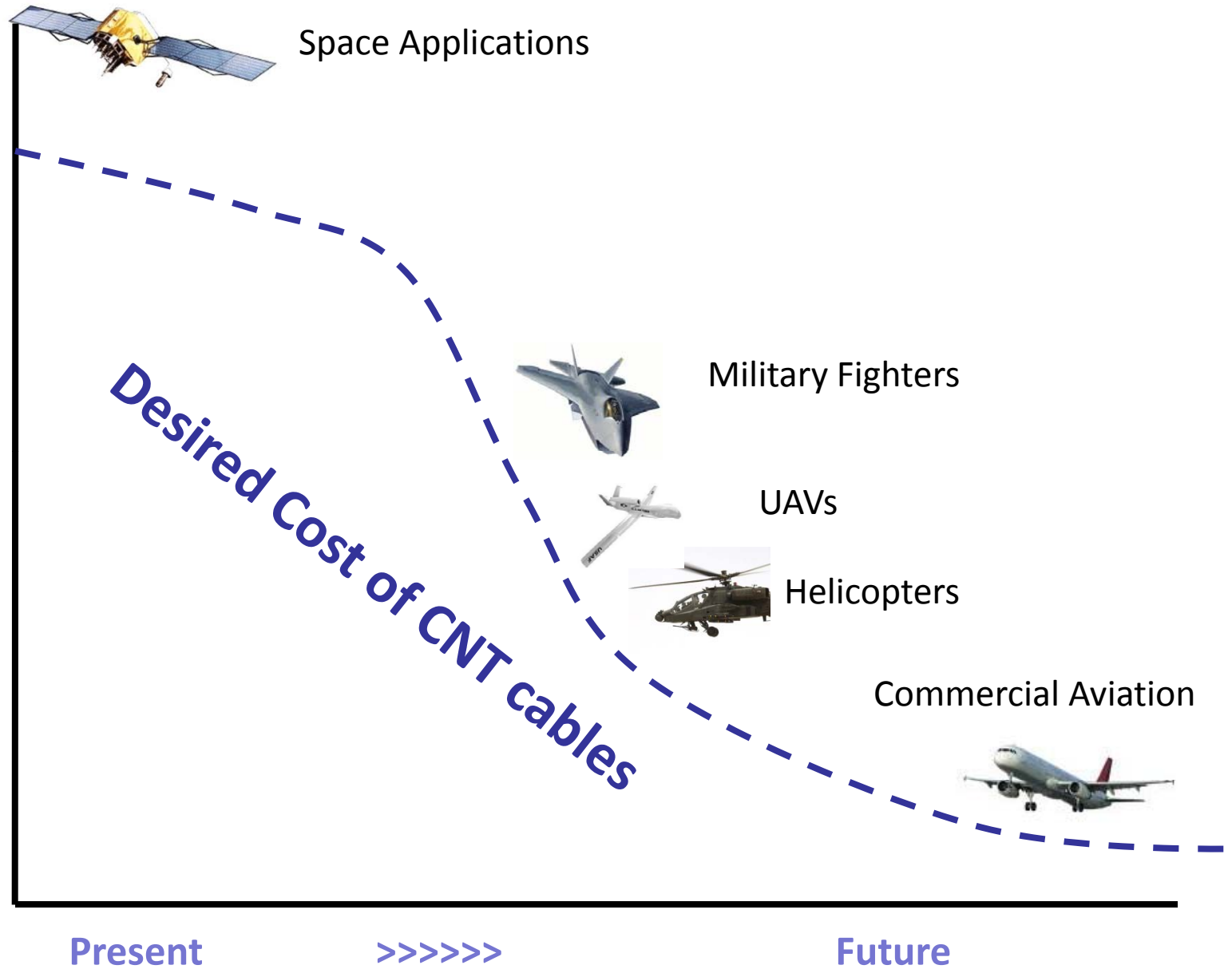


“Lightweight CNT Cables” CNT Cost



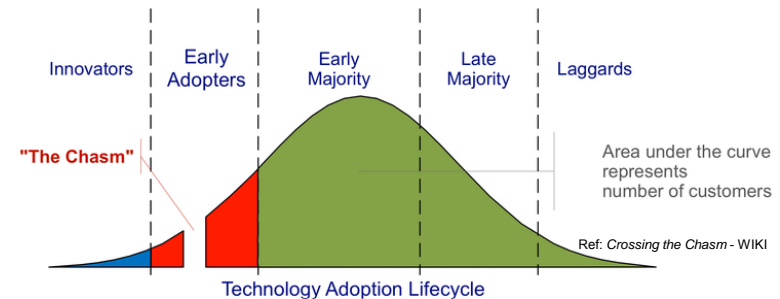
- **Estimated cost of a CNT modified aerospace cable is presently high (n x COTS), whereas, an aerospace coax COTS equivalent is typically <\$5/ft.**
- **CNT presently has potential application in shielding, low signal and data communications.**
- **The CNT commodity market may be very similar to semiconductor evolution? When will price drop?**

Lifecycle savings per pound of weight reduction



“Lightweight CNT Cables”

CNT Commodity Cost vs Value Proposition



- Present cost of CNT material is high, not unusual to “early adopters” of any innovative technology... *flashback* ... silicon to integrated circuits ... are we at “The Chasm”...?
- CNT insertion into high valued markets enables commercial market development
- Cost benefits are high in aerospace markets:
 - **Satellites:** *weight savings equates to launch cost savings*
 - **UAV's:** *weight savings equates to mission time*
 - **Aircraft:** *lifetime cost savings for an aircraft is equated from fuel savings*



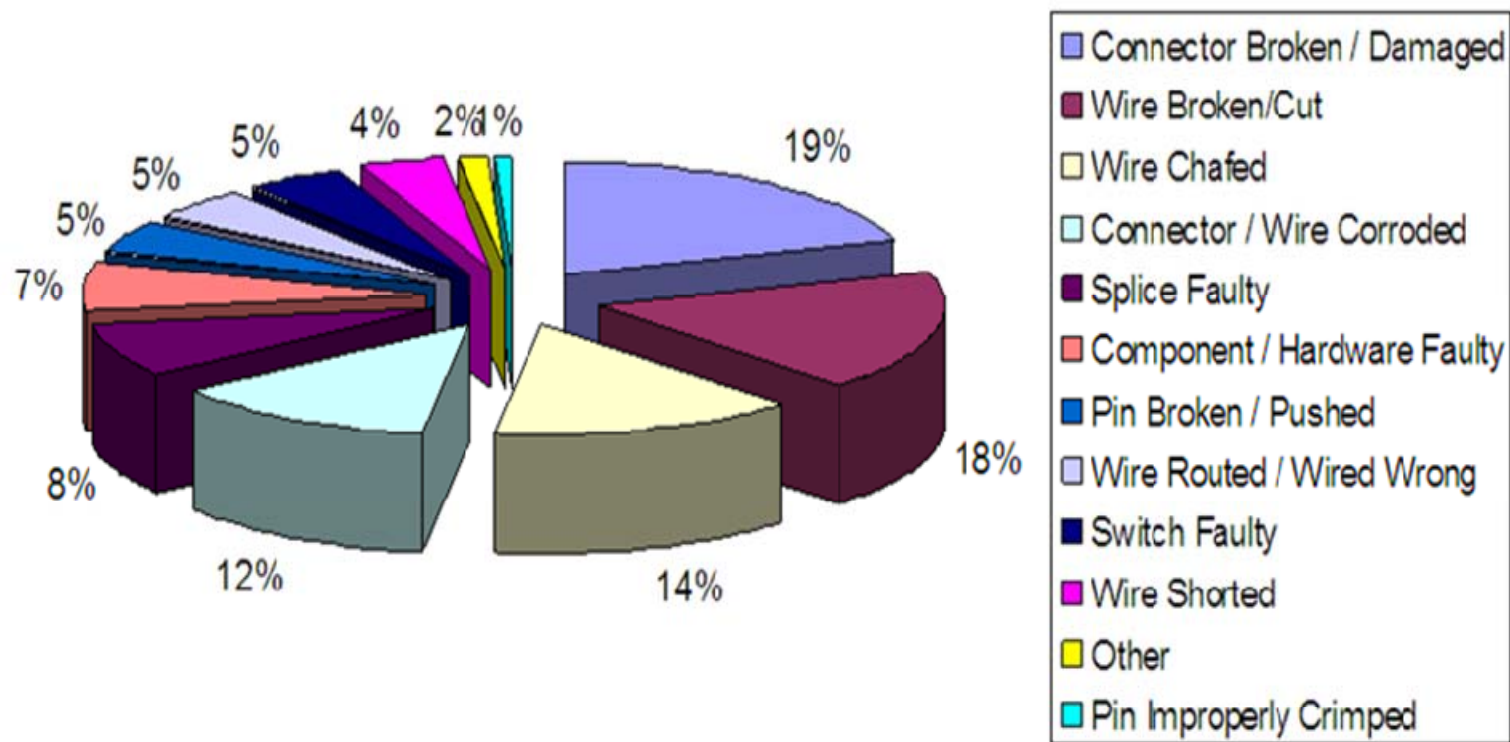
**“Lightweight CNT Cables”
Prototype CNT Cables**



**The following is
representative of our
background in wire integrity
... appropriate for
aerospace wiring quality.**

HISTORY OF WIRE INTEGRITY

TYPICAL WIRE FAILURE MODES



Source: US Coast Guard Aging Aircraft Branch



HISTORY OF WIRE INTEGRITY

SAFETY ISSUES RISING COMMERCIAL AIRCRAFT

- CATOSTROPHIC CRASHES
 - TWA 800 IN 1996 IN NY DUE TO FUEL PROBE ARC FAULT
 - SWISS AIR 111 IN 1998 NOVA SCOTIA DUE TO COCKPIT WIRE ARC FIRE
- NUMEROUS MISSION CRITICAL EXAMPLES:
 - 10/2000, Continental Flight 1579, DC-9, electrical fire
 - 8/2000, AirTran Flight 913, DC-9, electrical fire
 - 1/9/98, United Airlines 767-200, electrical fire
 - 7/5/97, Northwest Airlines DC-9-15, electrical fire
 - 6/17/97, Sun Country Airlines, DC-10-10, smoke in aircraft
 - 2/20/97, Northwest Airlines DC-9-15, electrical fire
 - 1/11/96, Colombian DC-9-14, in-flight fire, fatal accident
 - 6/5/96, Delta Airlines 767-225, electrical fire
 - 6/6/96, Continental Express Beech 1900, in-flight fire
 - 9/5/96, Federal Express DC-10-10, smoke in cabin
 - 12/11/96, US Air 757-225, In-flight fire



DEVELOPMENTS TO IMPROVE WIRE INTEGRITY PERTINENT TO AEROSPACE WIRING



GOAL:

Exceed the tensile strength and flex life of COTS stranded copper wire by braiding. Finished wire has same electrical conductivity and insulations but would be superior in fatigue resistance.

- Wires of metal content including cadmium, beryllium, 2 alloys, tin copper and silver copper wire represent the core of COTS cables today.
- Insulations included PFA, ETFE, XL-ETFE, Kapton wrap and sinter and PTFE
- 28 to 18 AWG by electrical equivalence
- Standards: 810F, 461E, 464, 4372 wire performance, 4373 wire test methods, 915-C flex, B470 bare wire
- Volume flex test capabilities necessary because there is a wide standard of deviation



Minnesota Wire Commercialization Strategy



QUICK LOOK AT MNW/MND COMMERCIALIZATION STRATEGY BASED ON R&D CONTRIBUTIONS



Hybrid Conductor Development



Performance Attribute	Market Value	Global Initiative
Light weight	Energy Savings, Payload Expansion	<u>Potential of CNT over traditional copper:</u> <ul style="list-style-type: none"> •Energy Efficiency <ul style="list-style-type: none"> •Raw material manufacturing •transportation •Green for Environment <ul style="list-style-type: none"> •Carbon footprint •Recyclable •Competitiveness (Payload expansion)
Flex life & Strength	Reliability, Life Cycle Extension	Advanced Technology Competitiveness
Radiotranslucence	MRI & Imaging Compatible	Health Care Costs, Quality of Life
Inflammability & Heat Dissipation	Light Weight Flame Retardancy, Low IR Emission	Safety, Life Saving, Insurance Cost Reduction
Corrosion Resistance	Reliability, Life Cycle Extension	Advanced Technology Competitiveness
High Conductive Nano Coatings (low volume, low weight)	Prognostic Health Management	Safety, Life Cycle Cost Reduction, End of Life Prediction

“Lightweight CNT Cables”

Applications for CNT Component Cables





“Lightweight CNT Cables” CLOSURE



**THANK YOU FOR YOUR
TIME AND ATTENTION!**

- DISCUSSION?
- ACTION ITEMS?

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